Condition Assessment of Power Transformer Onload Tap Changers Using Wavelet Analysis and Self-Organizing Map: Field Evaluation

Pengju Kang and David Birtwhistle

***Abstract*—An onload tap changer (OLTC) is the most maintenance intensive subassembly on a power transformer. Vibration monitoring is an effective technique that can be used to assess the condition of an OLTC nonintrusively. The authors have developed a condition monitoring system for common types of OLTCs that enables the condition of tap changer contacts and associated drive system to be inferred from vibration signals. A number of prototype systems have been installed onto OLTCs in distribution zone substations for field trials. Particular emphasis has been given to the detection of faults in a particular type of older tap changer that had been prone to a range of faults associated with the switching contacts and drive mechanism. For this type of tap changer, it has been shown to be possible to determine not only that the tap changer is aging but also to identify the particular part that is degrading.**

***Index Terms*—Condition assessment, fault detection, onload tap changer (OLTC), self-organizing map (SOM), wavelet transform.**

I. Introduction

An onload tap changer (OLTC) is the only moving part of a power transformer, and causes the majority of transformer failures in service [1], [2]. The condition assessment of OLTCs is important for ensuring the reliability of transformers. Vibration monitoring as a noninvasive technique has been found to be useful for the condition assessment of OLTCs of different manufacturers [3]–[6]. As part of an industry funded project, a condition monitoring system for commonly used tap changers was developed by the authors [2]. The condition monitoring system has the functions of automatic signature acquirement, on-line analysis of signatures, detection of faults occurring in the equipment, and remote control capability for down loading signatures for close examination.

A numerical procedure has been developed using the wavelet transform for processing and analysis of vibration signatures produced by the operation of tap changers [3], [4]. This paper describes the results of field studies made to increase confidence in the use of the monitoring system and to explore the application of the monitoring system as a maintenance tool. The approach that has been taken has been to monitor a tap changer in a period before maintenance and to prepare an assessment of the condition of the tap changer from data supplied by the monitoring system. The actual condition of the tap changer, as determined from the results of maintenance inspections, was then compared with the assessments based on results from the monitoring system. Tap changers have also been monitored for a period after maintenance to observe the effects of corrective maintenance. Generally, the results of this exercise show that the monitoring system can accurately predict the condition of tap changers.

The condition of two tap changers was monitored over a long period to observe how the condition of the tap changer gradually deteriorated. This paper demonstrates that with the use of the monitoring system it is possible to detect impending failures at an early stage, and it is possible to defer maintenance of tap changers when the monitoring system indicates minimal wear.

All of the vibration data presented in this paper were recorded using the monitoring system installed on resistance type tap changers externally mounted on the main tank of transformer. Electrically, this type of tap changer is connected to the high voltage side of the transformer, and the technical details of this type of tap changer have been described in [3] and [4].

II. Signal Processing and Analysis

A. Condition Diagnostic Indicators

A typical vibration signature caused by the contact movements of a resistance type tap changer mainly consists of a series of sharp vibration bursts, which correspond to specific contact movements. As discussed in our previous publication [3], this type of vibration signature is best analyzed in the time domain, and the condition of the equipment can be evaluated through the examination of several condition diagnostic indicators, such as the number, timing, and strength of bursts.

In order to reduce the random variation of signal amplitudes caused by noise, the envelope of measured signals are normalized before further analysis according to

$$x = \frac{x_0}{\sqrt{\sum_{i=1}^{n} |x_0(i)|^2}} \tag{1}$$

where x is the normalized signal, x_0 is the original signal, and n is the total number of samples in x_0.

The first-order derivative of the envelope of a vibration signal may be used to locate sudden increases in waveform amplitude.

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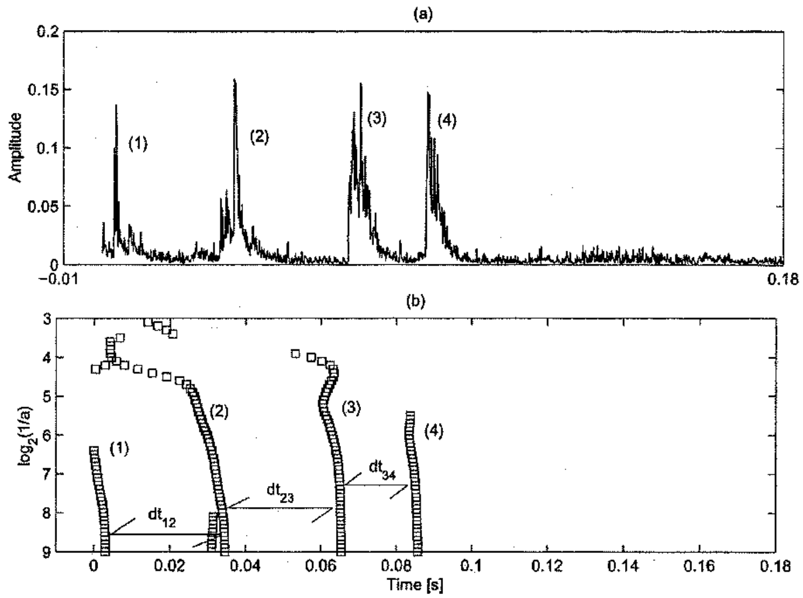

Fig. 1. (a) Envelope signature of normal condition of a resistance type tap changer operating from tap 7 to 8. (b) CWT ridge plot of the envelope signature.

Peaks in the first order differential curve of the envelope indicate the start of sudden transient bursts. However, when the signal is contaminated with noise, it is well known that differential-based method give inaccurate results. The wavelet transform as a multiresolution differential operator decomposes the first order differential of the original signal into a time scale structure with different resolutions. In this way the noise in the differential curve can be decoupled from the true curve. For this purpose, it is necessary to use a wavelet with one vanishing moment. A wavelet $\psi(t)$ with one vanishing moment can be expressed as the first-order derivative of a fast decaying function $\theta(t)$ referred as the scaling function [7], [8]

$$\psi(t) = \frac{d\theta(t)}{dt}. \tag{2}$$

As a consequence of a single vanishing moment, the continuous wavelet transform (CWT) can be written [7], [8] as

$$\mathrm{CWT}_\psi(a, b) = a\,\frac{d(x * \theta_{ab})}{dt} \tag{3}$$

where

$$\theta_{ab} = \frac{1}{\sqrt{a}}\,\theta\left(\frac{t-b}{a}\right).$$

The symbol $*$ in (3) represents the convolution operation between x and θ_{ab}, and b is the shift factor of the wavelet on the time axis. The resolution of the wavelet transform is adjusted by changing the value of scale factor a. The local maxima of the wavelet transform are the maxima of the first order derivative of the function x smoothed by the function $\theta_{ab}(t)$. The quadratic spline wavelets with one moment were selected as the analyzing functions for OLTC vibration signatures [3], [4].

A rising edge is defined as the sudden increase in the amplitude of vibration signature, which indicates the occurrence of a vibration burst. If a vibration signature produces a rising edge at t_0, then a plot of the modulus of the wavelet transform coefficients of the envelope of the signal consists of a vertical line of maxima converging to t_0 when the scale becomes finer [the value of scale a in (3) is smaller] [7], [8].

A set of vertical maxima lines is defined as the vertical ridges of CWT, which gives information about the number of bursts in a vibration signal, and the timing between bursts. The strength of a burst describes the steepness and height of the sudden rise in the amplitude. The strength of a burst δ can be characterized in the wavelet domain as

$$\delta = \int a\,|CWT_\psi(a, b)|\; da. \tag{4}$$

The effect of noise has negative consequences on the localization of bursts by introducing uncertainty into the position of local maxima across all scales. These maxima produced by noise were removed by truncating the local maxima against a predetermined threshold [3], [4].

Fig. 1(a) shows the envelope of a vibration signature of a resistance type tap changer, and the corresponding CWT ridge plot of the envelope is given in Fig. 1(b). The measured vibration signal was initially in volts and was proportional to acceleration. As this signal was normalized following Equation (1), the vibration signals shown in this paper are dimensionless unless specified. The ridge plot shown in Fig. 1(b) is a two-dimensional (2-D) display of dominant local maxima of the CWT performed on the normalized envelope signal shown in Fig. 1(a) at different time and scale values. The detailed procedure of obtaining the ridge plot can be found in [4]. Each ridgeline in Fig. 1(b) represents the occurrence of a vibration burst in the original signal.

As can be observed, the vibration signature of this type of OLTC contains four dominant transient bursts, shown as busts (1)–(4) in Fig. 1(a), and there are four dominant ridgelines, as shown in Fig. 1(b). The condition indicators for this type OLTCs have been established as: $[\delta_1, \delta_2, \delta_3, \delta_4, dt_{12}, dt_{23}, dt_{34}]$, where $\delta_1, \delta_2, \delta_3, \delta_4$ are the strengths of bursts 1 to 4 respectively defined in the wavelet domain [see (4)], and $dt_{12}, dt_{23}, dt_{34}$ are the time delays between the designated bursts. At higher scale values in the ridge plots, times may be

TABLE I
CONDITION INDICATORS FOR THE NORMAL CONDITION OF THE TAP CHANGER

Burst No	1	2	3	4
δ	16.9	25.6	46.3	40.3
dt (ms)	31.5	31	20.3	

in error, caused by poor localization accuracy of wavelets of coarse resolution, but as scale is decreased the times converge to the correct values. Therefore, the time delays were extracted using the CWT values of the envelope signal at a lower scale value (e.g., $1/a = 8.5$). The procedure for the time indicator extraction has been presented in [3], [4]. These condition indicators may be used to diagnose the actual physical condition of the tap changer. The values of the condition indicators for the signature shown in Fig. 1 are given Table I.

B. Overall Condition Indicator

A by-product of the wavelet procedure is that we can get a smoothed envelope from the CWT of the original envelope using the scaling function θ_{ab}

$$\mathrm{CWT}_{\theta}(a, b) = x * \theta_{ab}. \tag{5}$$

The operation given in equation (5) is a progressive smoothing of the input signal $x(t)$. Therefore, the wavelet transform of a noisy envelope of a vibration signal at a predetermined scale value is the smoothed envelope. Fig. 2 shows the smoothed envelope of a vibration signature of a resistance type OLTC for tap operation from 7 to 8. The smoothed envelope will be used for automatic detection of the changes in the shape of the envelope that is caused by faults developed in a tap changer.

The self-organizing map (SOM) [10], [11] is a convenient tool for mapping complex data in multi-dimensional space into 2-D clusters while preserving the inherent topological relations among the input feature data. The map is created in an unsupervised way known as competitive learning [10], [11] from the input feature data. The training algorithm for SOM is given in Table II.

Training of the SOM takes place in two principle phases: the ordering and the fine-tuning phases [11]. The ordering phase takes place first. During this stage, the topological ordering of the map units takes place. The learning rate η in the ordering phase is maintained relatively large. Initially, η is selected close to 1.0. Upon finishing the first training phase, η will not be typically reduced below 0.1. During the fine-tuning stage, the map units are adjusted to closely match the distribution of the input data. To this end, a much smaller value for both learning rate and neighborhood function is desirable. Typically, η is selected to be 0.01 or less. Normally, the initial neighborhood size is set to half of the size of the competitive layer. The neighborhood size is exponentially reduced to 0 when 10% of the maximum iteration is reached.

Although a SOM can handle temporal shifts in the signals, unaligned envelope signatures require a SOM with a large map size to generalize the differences in the time shifts between envelopes caused by the data acquisition system. Good signal alignment improves the SOM's generalization performance. Auto-correlation of the envelope is used to realize automatic shift alignment. The auto-correlation of a smoothed envelope x is given by

$$R_{xx}(\tau) = \frac{1}{n} \sum_{i=0}^{n-\tau-1} x(i-\tau)x(i), \qquad \tau = 0, 1, 2, \ldots, n-1. \tag{6}$$

The normalized auto-correlation is given by

$$r_{xx}(\tau) = \frac{R_{xx}(\tau)}{R_{xx}(0)}, \qquad \tau = 0, 1, 2, \ldots, n-1 \tag{7}$$

where $R_{xx}(0)$ is the auto-correlation at zero lag. The normalized auto-correlations of all the envelope signatures are automatically aligned at the maximum point—the 0th lag correlation.

Given a feature pattern $F = r_{xx}$ and a SOM trained using the r_{xx} feature patterns of signatures of a newly-maintained tap changer, the minimum quantization error (mqe) for this data set is defined as the minimum Euclidean distance between F and all of the weight vectors (w_j)

$$mqe = \min \|w_j - r_{xx}\|. \tag{8}$$

Extremely high mqe values may occur for two reasons: either there are outliers in the data set, or the datum belongs to a fault class.

There exist several possible modes by which a tap changer may fail:

1) sudden failure;
2) spasmodic changes before failure;
3) gradual degradation.

Faults by failure mode 1 and 2, such as a broken component, will cause a sudden increase in the value of condition indicator mqe. Faults of failure mode 2, such as contact wear, will normally cause the mqe to gradually drift upward as shown in Fig. 3. The mean value of the mqe undergoes a monotonic process: a series of upward shifts, $\mu_1, \mu_2 \cdots \mu_{n-1}$, before it approaches the critical value, μ_c, after which faults may start to develop in the OLTC. When the mean is below μ_c, the OLTC is regarded as being in normal condition. As soon as μ_c is exceeded, an alarm should be raised with minimum detection delay τ_D so that field personnel can be notified and remedial actions are to be taken on the faulty tap changer. As long as the mean is under μ_c, the equipment is deemed to be in a normal condition.

The up-drift mean path of the raw mqe samples is estimated using restricted regression in which the distance of raw data samples from the mean path is minimized subject to the monotonic constraint

$$\min \sum_{i=1}^{n} \sum_{j=1}^{m_i} \|mqe_{ij} - \mu_i\| \quad \text{subject to } \mu_1 \le \mu_2 \le \cdots \le \mu_n \tag{9}$$

where n is the number of subgroups into which the original data series is divided, m_i is the number of mqe samples in the subgroup i, and $\mu_1, \mu_2 \cdots \mu_n$ are the corresponding mean values of

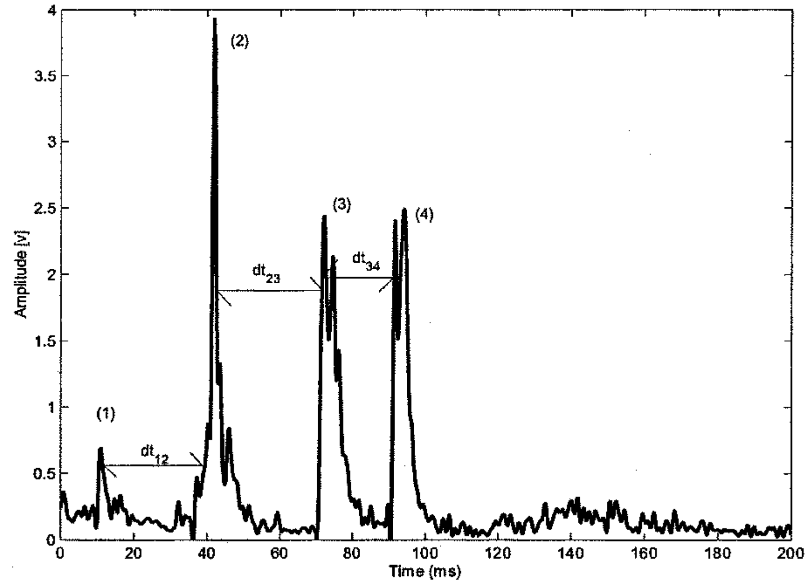

Fig. 2. Wavelet smoothed envelope of the vibration signature of a resistance type tap changer operating from tap 7 to 8. The amplitude of the envelope shown is not normalized.

TABLE II
TRAINING ALGORITHM OF SOM

1. Initialise the weight vectors $w_j(0)$, the learning rate $\eta(0)$, and neighbourhood function $\Lambda_{i(F)}(0)$.
2. Present each training feature vector F to the input layer of the map and determining the wining neuron in the competitive layer using the Euclidean criterion. The index of the winning unit will be: $i(F)$ =n, when $\|w_n - F\| \leq \|w_j - F\|$
3. Update the weight matrix. $w_j(k) = w_j(k-1) + \eta(k)[F - w_j(k-1)]$ if $j \in \Lambda_{i(F)}(k)$; $w_j(k) = w_j(k-1)$ if $j \notin \Lambda_{i(F)}(k)$
4. Update the learning rate $\eta(k)$, and shrink the neighbourhood function $\Lambda_{i(F)}(k)$.
Repeat steps 2 to 4 until the stop condition is satisfied.

the n subgroups. A numerical algorithm known as "pool-adjacent-violators" [12] is available for finding the maximum likelihood estimate of the mean path. This algorithm works in an iterative way by arranging the data sequence into a number of subgroups until the monotonic mean change is no longer violated.

The automatic fault detection procedure uses the overall condition indicator mqe to indicate the global progressive deviation of the present signatures from those of newly maintained equipment. The condition degradation of the contacts can be visualized by following the trend of the mqe. A limit for mqe is set according to the data of known fault conditions. Once the limit for the global condition indication is surpassed, a warning is issued. After that, the signatures will be down loaded to an office PC via telephone connection, where they can be examined in detail. The actual diagnosis of the tap changer condition is conducted using individual condition indicators: the number, the delay time, and the strength the major bursts in vibration signatures.

III. FIELD EVALUATION

A. Gradual Degradation

A monitoring system was connected to a resistance type tap changer in a distribution substation immediately after the equipment was maintained. This system has been continuously monitoring the condition of the tap changer for an entire maintenance period scheduled under a time based maintenance regime. The hardware capability of the monitoring system has been given in [3]. The monitoring system records the vibration signal each time OLTC changes the taps in either up or down directions. The condition assessment of contact condition has to be tap position dependent, since the vibration signatures of different tap positions can be different. Each vibration envelope signature has 2000 samples. In this monitoring cycle, there were no abrupt faults detected in the OLTC. However, the monitoring system indicated a trend of gradual degradation of contact condition, which was observed from the gradual changes in the time delays between the four vibration bursts in the vibration signatures of taps in frequent use. We correlated the rate of change in the delay times with the number of tap operations and found that the more tap operations made on the taps, the greater the changes appearing in the corresponding time delays. We have found that the strengths of the vibration bursts remained constant in this maintenance cycle of this OLTC.

Fig. 4 shows the changes in the mean paths of the mqe and the delays in the time between vibration bursts for the signatures of a resistance type tap changer operating from 7 to 8 for a period of 2787 operations. This overall condition indicator shows monotonically increasing trend with respect to the gradual degradation of contact condition. The overall condition indicator mqe is used to automatically initiate the need for closer inspection of vibration signatures. The critical mean value μ_c for this type of OLTC has been determined to be 4.50 from the data of controlled experiments as well signatures recorded before and after maintenance. The present mqe value is 36% of its critical value.

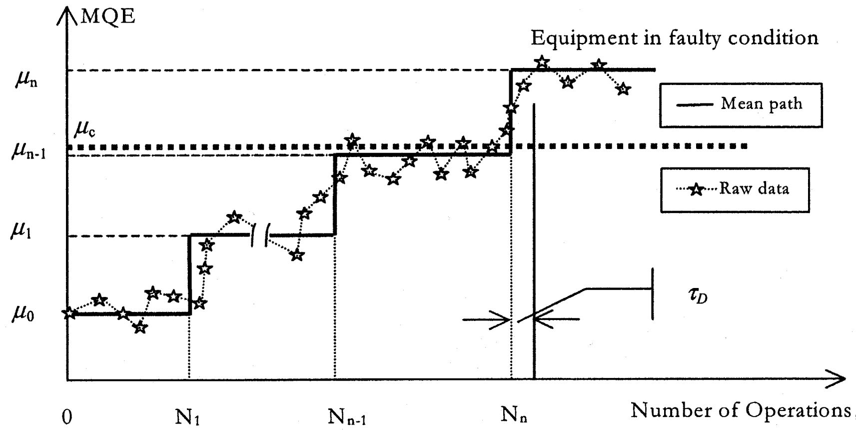

Fig. 3. Schematic illustration of gradual degradation of contact condition of resistance type tap changers.

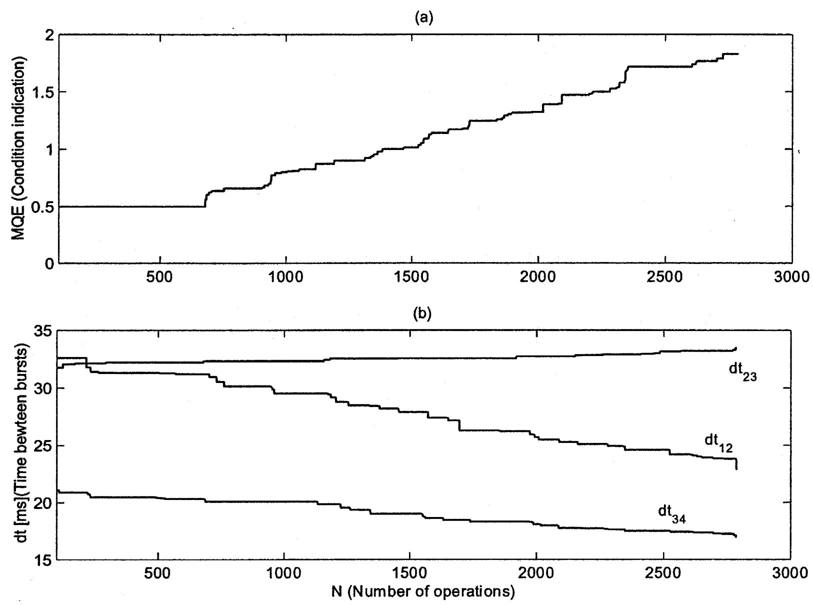

Fig. 4. (a) Plot of the mean path of the overall condition indicator against the number of operations. (b) Plot of the mean paths of the timing condition indicators against number of operations.

TABLE III
TIME INDICATORS EXTRACTED FROM THE SIGNATURES OF NEWLY MAINTAINED OLTC AND FROM THE SAME EQUIPMENT AFTER 2787 OPERATIONS

	Newly maintained	Due for maintenance	Rate of change (Dg) in %
No of operations	1	2787	
dt_{12} [ms]	34.02	22.90	Dg_{12} = 32.65
dt_{23} [ms]	30.26	33.47	Dg_{23} = -10.65
dt_{34} [ms]	21.10	17.00	Dg_{34} = 20.00
dt_{14} [ms]	85.38	73.37	Dg_{14} = 14.07

Table III gives the results of changes in the timing of the bursts in the vibration signatures for the resistance type tap changer operating from 7 to 8. We define Dg as the rate of change in time delay related to the value for a newly maintained OLTC. This rate of change of the time delay indicator is given in the fourth column of Table III. The values of Dg are related to the degree of contact wear, and we have been able to correlate the values of Dg with contact degradation. The data used in this correlation was obtained by conducting controlled experiments while observing rate of contact wear [4] and by acquiring signatures before and after maintenance. Using the signatures of wear conditions, we have also been able to correlate the values of the condition indicator mqe to different wear conditions for a common type of tap changer.

Fig. 5 shows the CWT ridge plot of a vibration signature of a resistance type OLTC immediately after previous maintenance and the corresponding ridge plot after 2787 operations. Small changes in timing of the major bursts after over three year's operation are observable in the CWT ridge plots. However, the strengths of the four bursts were found to remain constant over the entire monitoring period of this tap changer. This is due to the fact that the degree of contact wear has reached approximately 36% of its allowable wear limit. The maintenance crew later confirmed that the actual physical degree of contact wear is comparable with the estimation made from the monitoring data. It has been demonstrated that with the help of the monitoring system, the maintenance of OLTC can be scheduled at a later time until the remaining life of the contacts has been reached.

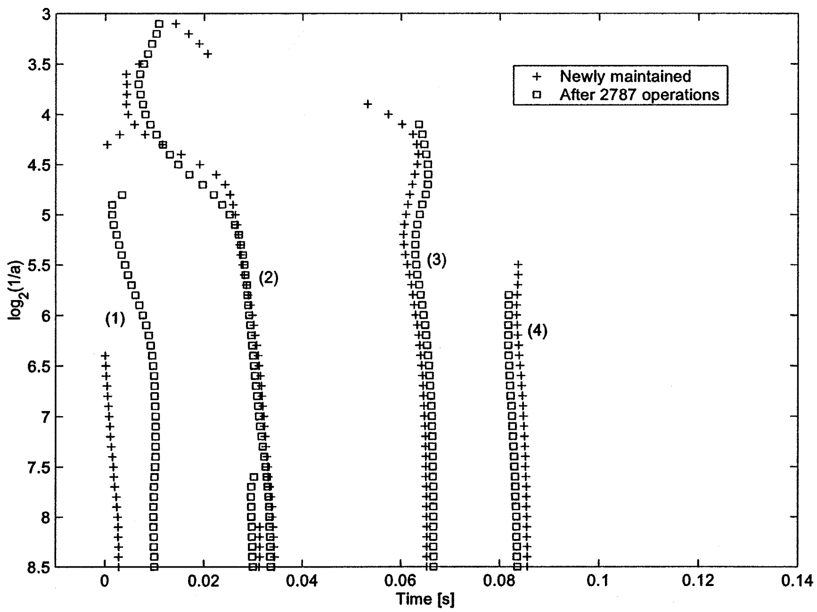

Fig. 5. Comparison of CWT ridge plots of a newly maintained resistance type OLTC and the same equipment after 2787 tap operations from 7 to 8.

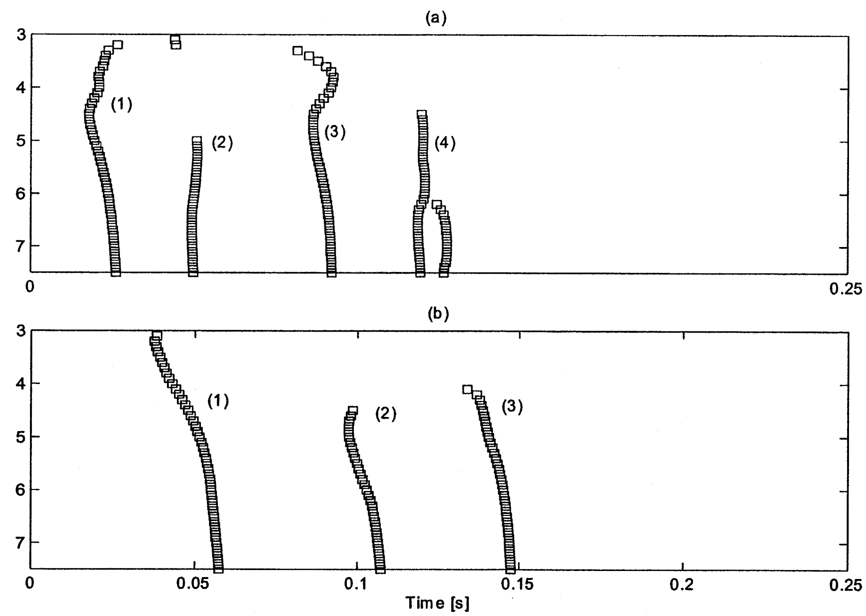

Fig. 6. (a) CWT ridge plot of a signature of good condition. (b) CWT ridge plot of a signature of abnormal condition.

B. Sudden Changes in Vibration Signatures

Fig. 6(a) shows a typical CWT ridge plot of vibration signature of another resistance type tap changer measured immediately after the maintenance. This is a typical signature obtained for the tap changer operating from tap 7 to 8, and is considered to be the signature of the tap changer in normal condition. The monitoring system gave a warning 6 mo after the maintenance that there were occasional abnormal signatures. A typical CWT ridge plot of an abnormal signature is shown in Fig. 6(b), in which, one of the four-bursts normally appearing in the normal signature is missing. The abnormal signature occurred in signatures of all tap positions.

It appeared that there were significant changes in the contact operating sequence leading to abnormal signatures. It was hypothesized that this could be due to slipping of the tap changer drive shaft. At that stage, the rate of occurrence of the abnormal signatures appeared to be constant (not increasing). There was a concern that the abnormal contact sequence could be causing changes to the tap changer condition and might lead to catastrophic failure. It was therefore recommended that the tap changer be inspected at the earliest opportunity.

When field crew disassembled the drive wheel shaft, the slippage in the shaft was identified in the key and keyway of the Geneva wheel. There was about 1–2 mm of play within the keyway, which, when taken at the extremities of the moving contacts, equated to approximately 40 mm of play. Considering that the distance between the fixed contact is about 50 mm if this condition were left unchecked then a failure would have been inevitable.

C. Deferral Maintenance

In another case, a tap changer of the same type, had been inspected during maintenance three times in the past, and on each occasion, no degradation was observed. In the most recent inspection, the tap changer was monitored before the scheduled maintenance, and the condition indicator of the monitoring system was found well below the alarming threshold. This indicated that the equipment was still in a healthy state. Subsequent maintenance inspections showed that the predication made by the monitoring system was correct. In this case, three field maintenance activities could have been deferred by application of the monitoring system.

IV. Conclusions

It has been demonstrated in more than 3 yr field experiences that vibration monitoring is an effective tool for assessing the condition of tap changers. The overall condition indicator mqe, the deviation of auto-correlation vector of the newly acquired envelope signature from the reference auto-correlation patterns, was used to provide a single index to detect faults automatically in the OLTC. This index can be directly sent to the asset management system to trigger alarms such that maintenance staff can examine the signatures closely and make decisions on the true condition of the tap changer. For the type of OLTC under our investigation, we used signatures of 50 operations at each tap position to establish the reference patterns. The patterns were reestablished after maintenance. However, the reestablished patterns were screened against the reference patterns to ensure that the maintenance was conducted properly. The reference patterns were obtained using controlled experiments on a de-energized OLTC. According to our field experience, the shape of online and offline OLTC signatures were very similar, and the main difference between them was that the amplitude variation of the online signatures was slightly larger than that of offline signatures.

The condition diagnosis was carried out with the help of a few condition indicators including the number, strengths, and the timing of the bursts. The timing indicators have been proven to be useful for the estimation of degree of contact wear, and the appearance of spurious bursts or disappearance of one or more bursts in the signature have indicated the occurrence of faults in the driving mechanism, which can have serious consequences if unattended. The change of the burst strength is not significant until the contacts have reached later stage of their useful life, and at least 20% reduction in burst strength of signatures of extremely worn contacts has been observed. Other faults such as weak tension springs in the driving mechanism will cause both the strength and timing indicators change significantly.

The work reported in this paper is related to the field application of vibration monitoring to a type of OLTC extensively utilized in Australian utilities. It has been shown this monitoring system is effective to detect faults of mechanical nature in the driving mechanism and contact assembly of the OLTC. The methodology presented is also applicable to tap changers of other types. The main practical issue regarding the use of the technique is the establishment of reference vibration patterns. To apply the monitoring system on a different type of OLTC, it is necessary that controlled experimental study be conducted to understand the vibration mechanism of the tap changer under different fault conditions.

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